Japanese Psychological Research
THE JAPANESE PSYCHOLOGICAL ASSOCIATION

Japanese Psychological Research
2018, Volume 60, No. 4, 196–224
Special issue: fNIRS in Psychological Research

doi: 10.1111/jpr.12207

Invited Review

Toward Interactive Social Neuroscience: Neuroimaging Real-World Interactions in Various Populations[1]

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Abstract: Human social activity is a continuous dynamic behavior consisting of live social signal exchanges; thus, studying interactions among multiple humans is critical to understanding social cognition. Indeed, social neuroscience focusing on such aspects—*interactive social neuroscience*—is an emerging field of interest. Functional near-infrared spectroscopy (fNIRS) has played a significant role in accelerating this field by enabling real-world neuroimaging for various populations. The present paper will first review previous hyperscanning studies using functional magnetic resonance imaging (fMRI), magnetoencephalography (MEG), and electroencephalography (EEG). We will then summarize attempts and findings of fNIRS hyperscanning studies on social interaction in adult populations. Finally, we will review recent investigations of interactive social neuroscience in young populations and show preliminary results from a mother–infant hyperscanning study. These studies have predominantly revealed synchronized brain activities between humans and have identified conditions in which such inter-personal connectivity was found to be increased. Furthermore, these studies suggest possible mechanisms of inter-brain coupling: a process that recruits both mirror system and mentalization networks. Although fNIRS hyperscanning of infants remains limited, the reviewed literature demonstrates significant potential for fNIRS to disclose the interactive social brain and its development.

Key words: hyperscanning, functional near-infrared spectroscopy, synchronization, entrainment, social neuroscience.

Studying the single human brain places limitations on identification of human social cognition capacity, as social cognition is a psychological process to cope with another's mind, such as inferring another's intentions, feelings, and thoughts (Adolphs, 2009). Human social activity is a dynamic process that is triggered by others and is initiated to others by way of eye gaze, facial and body expressions, language, speech, and various perceptual signals. Thus, the presence and/or relationship of other agent(s), whether visible or not, with a targeted human is a prerequisite to social cognition. Previous neuroimaging studies have attempted to

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[1] This work was supported by grants from the MEXT Supported Program for the Strategic Research Foundation at Private Universities, Grant-in-Aid for Scientific Research (KAKENHI; 15H01691), and JST/ CREST (social imaging).

[2] We thank E. Hoshino, M. Asano, and M. Hata for their kind help with the preliminary study. We also thank K. Higuchi for automatic behavioral estimation used in Figure 1.

investigate the human social brain using prerecorded stimuli that simulate other individuals. For instance, cerebral activities and connectivity have been measured in response to facial stimuli, emotional stimuli, and social stories. Indeed, these cerebral responses reflect part of the social cognitive process, and such findings are vital to our understanding of social cognition at present. Nonetheless, such methods only allow for observation of certain brain mechanisms and provide a snapshot of social behavior.

Social activity is a continuous interactive behavior consisting of live social signal exchanges. Such interaction is core to human social behavior. Its significance is exemplified by a hypothetical mode called *we-mode*, which is realized exclusively through person-to-person interaction. During interactive we-mode, the cognitive subject is shifted from *me* to *we*, and information processing for others is highly accelerated (Gallotti & Frith, 2013). In the field of social neuroscience, the emergence of unique terms, such as *second-person neuroscience* and *two-in-one* systems, underscores the increasing significance of studying the brain correlates of social encounters (Konvalinka & Roepstorff, 2012; Schilbach et al., 2013). Therefore, capturing such social cognitive processing from real continuous interaction between agents is crucial to advancing the field, as it may uncover novel evidence for social neuroscience. In particular, simultaneous recording of two brains (i.e., hyperscanning) during such interaction provides the most accurate means by which to clarify the two-in-one system of the human social brain.

A series of functional magnetic resonance imaging (fMRI) and electroencephalography (EEG) studies has been conducted investigating human interaction primarily via hyperscanning, as reviewed in the next section on adult populations. However, since 2011, functional near-infrared spectroscopy (fNIRS) neuroimaging in a live social setting or hyperscanning of human interaction has been stably expanding and appears to provide unique insights into social neuroscience. The fNIRS technique is innocuous, portable, and silent (Hoshi, 2007; Minagawa-Kawai, Mori, Hebden, & Dupoux, 2008) and enables ecological experimental settings for performing interactive tasks in the real world (Figure 1). In particular, it provides the opportunity to measure the developing brain in infants and children, including those with atypical development, and may provide information crucial to understanding the origin and development of human social ability. The present paper chiefly reviews fNIRS studies on person-to-person interaction, focusing on the hyperscanning method performed on adult and young child populations. We will discuss advancements in this field and summarize the available literature with regards to the methodology and neuroscientific findings. In the

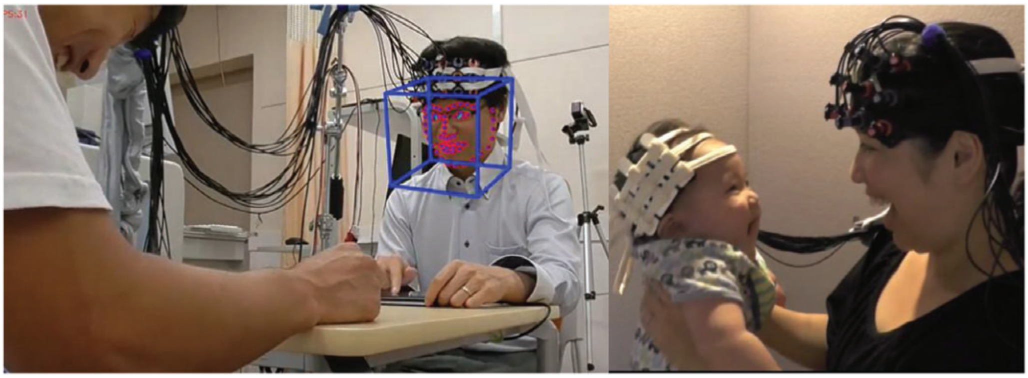

Figure 1 fNIRS measurement during face-to-face interaction task (left) and mother–infant interaction (right). For the adult experiment, automatic estimation of gaze and facial movement was applied to analyze with fNIRS data. We obtained permission from photographic subjects.

next subsection, the significance of live interactive stimuli in social neuroscience is discussed in terms of current literature on the development of social cognitive abilities. In the second section on studies on adult populations, we first review the hyperscanning studies performed by fMRI, magnetoencephalography (MEG), and EEG in comparison to fNIRS studies. EEG studies in particular have accumulated and provide various insights for those who will try fNIRS hyperscanning. After reviewing the hyperscanning studies with adults, we will focus on fNIRS studies on young populations using live social stimuli, in order to discuss the significance of live stimuli and the novel findings. Although infant–infant hyperscanning has not yet been performed, we will discuss recent findings obtained from hyperscanning of mother–infant interaction. These reviews may offer a view of fNIRS usage beyond the conventional fields, in addition to the potential of fNIRS in interactive social neuroscience. Finally, we will wrap up the review by discussing the mechanism of inter-brain coupling and current problems in this field to suggest future directions.

Interactive Live Stimuli and Their Significance

The use of live stimuli in social neuroscience is crucial to the advancement of the field in many ways. As mentioned above, non-live stimuli offer only a snapshot of social behavior. Even if the stimulus is a continuous video clip, researchers are only able to examine participants' responses to the unidirectional social stimuli. From the literature on developmental psychology, a phenomenon called *video deficit*, which pertains to difficulties of learning or performing via unidirectional video, is well known. While video deficit is observed in various behavioral processes, including language learning tasks, such as phoneme category and word, object searching task, and imitation task (Kuhl, Tsao, & Liu, 2003), this deficit may be explained by the differences between live and non-live stimuli, namely interactive and unidirectional stimuli. An alternative interpretation of video deficit is that perceptual and cognitive learning by young children and infants is facilitated by social interaction situations.

The advantages of performing either hyperscanning or single recording to determine the impact of live interactive stimuli involves four factors (a–d), categorized based on whether they are interactive or non-interactive and live or non-live. The factors and their respective amplitudes are recorded in Figure 2. Firstly, (a) enhanced sensory and perceptual amplitude of live stimuli is one of the advantages, as real humans usually provide stronger impressions in terms of size, three-dimensional information, and haptic and olfactory information than the monitor-presented ones. Employing live versions of stimuli does not merely positively affect this factor (Figure 2), but this factor (a) is influential enough to enhance the other three factors. (b) Contingency of live stimuli is also a crucial factor, as contingency provides rich social responsiveness that often serves as a reward. Quick response is a prerequisite to induce the experience of contingency. This may relate to a sense of ownership or agency as an immediate reaction to the initiator's behavior elicits the sense of "I control something," which may also induce a sense of unity. (c) The third factor, bidirectionality, is rather broad and includes various interpretations and consequences. Bidirectionality of live stimuli increases the stimulus impact, as a response signaled from the self somehow alters the behavior of others, resulting in elicitation of emotion and/or attention by him/herself. Its impact may differ

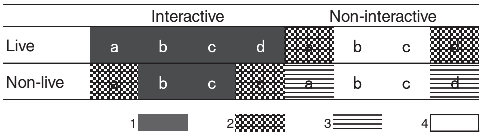

Figure 2 Amplitude of four factors contributing to experiments on social brain in different settings (live vs. non-live, interactive vs. non-interactive). Four factors are (a) sensory and perceptual characteristics, (b) contingency, (c) bidirectionality, and (d) presence of mind. The darker each square is, the higher each factor's amplitude (four levels, 1–4).

depending how and what the initiator (self) expects from the other's reaction. Hence, one important aspect of bidirectionality involves exchanges of feedforward and feedback. Previous studies on entrainment also suggest that there may be implicit bidirectional exchanges of sensory signals between agents. These sensory signals could be a visual cue (such as an eye blink, gaze movement, or body movement) or an auditory cue (such as speech). It is assumed that such implicit processing of perceptual cues contributes to the entrainment or synchronization phenomena (Chartrand & Bargh, 1999; Koike et al., 2016; Shockley, Santana, & Fowler, 2003). This implicit process may also relate to the mirroring system (e.g., contagious yawning). Depending on their quality of spatial and temporal resolutions, factors (b) and (c) can be effectively implemented using non-live stimuli. The fourth factor, (d) human presence, refers to a presence of mind that encompasses intention and emotion; it does not require the individual to react, and the experimental task need not involve any mentalization (Schilbach et al., 2010). Its impact differs depending on the relationship (e.g. *boss* or *friend*) and autobiographical background. The presence of mind itself serves as a high influential factor as has been extensively studied in the field of social psychology. *Social facilitation effect* and *social pressure* are typical examples of such studies. Such a state of the human mind may diminish in response to non-live stimuli, particularly non-interactive stimuli. However, as indicated by Figure 2, non-live stimuli still function effectively if they are interactive. Thus, hyperscanning—employing either live or non-live stimuli—demonstrates potential for exploring the two-in-one system.

Neuroimaging Social Interactions of Adult Populations

Hyperscanning Technique

The hyperscanning technique is a valuable method for observing neural activity underlying social cognition during person-to-person interaction. Although the word *hyperscanning* was first coined by Montague et al. (2002) in an fMRI study, the first hyperscanning study can be traced back to over 50 years ago using EEG (Duane & Behrendt, 1965). This dual-EEG study was designed to prove the existence of extrasensory perception between twins by calculating the correlation between their EEG traces. This paper has been criticized for poor statistical analysis and spatial resolution, but was the pioneering study that raised the notion of simultaneous acquisition of cerebral data from multiple participants (F. Babiloni & Astolfi, 2014). Hyperscanning does not necessarily pertain to simultaneous recording of persons in a live real-world setting; therefore, our review includes hyperscanning studies of adult populations using non-live stimuli, as these reports provide background information underlying current real-world interaction experiments.

fMRI Hyperscanning

After lying dormant for a long period of time, the multi-subject recording technique underwent a renaissance led by Montague et al. (2002), who were the first to apply hyperscanning to study multi-participant interaction using fMRI devices. In this seminal study, two players involved in a simple deception game were scanned simultaneously using two different fMRI devices situated over a long distance and connected via the Internet. This interactive game involved one sender and one receiver. Common activity was identified in the supplementary motor area of both players, but was observed to be stronger in the sender's brain. While this study demonstrated the technical feasibility of dual-fMRI scanning and first advocated the idea that simultaneous recording of both interacting brains could measure social interaction best, it suffered from small sample size (only three pairs) and significant time delays between the stimuli and the responses (Hari & Kujala, 2009).

Subsequently, Montague's group extended their hyperscanning fMRI techniques, using a set of turn-based neuroeconomic trust games, to reveal the neural underpinnings of various social cognitions, such as reciprocity (King-Casas et al., 2005) and agency (Chiu et al., 2008; Tomlin et al., 2006). Another study also applied fMRI hyperscanning to record two-brain activities related to the comparison of received rewards with partners (Fliessbach et al., 2007). Using recorded videos of each other's body gestures, speech, or facial expressions, other fMRI studies tackled unidirectional offline interaction by scanning two participants consecutively (Anders, Heinzle, Weiskopf, Ethofer, & Haynes, 2011; Schippers, Roebroeck, Renken, Nanetti, & Keysers, 2010; Stephens, Silbert, & Hasson, 2010). These studies utilized innovative experimental designs to investigate the neural activity underlying social interactions, and yielded impressive results. However, these experiments defined social interactions in the context of an information flow between the brains of senders and receivers in the order of seconds, and occasionally the paradigms were somewhat rigid with regard to the roles that each participant had to take (i.e., no changing roles during the experiment). These paradigms either focused on the single side (i.e., the receivers) of information flow, or failed to capture the moment-to-moment interactions between two persons. As a result, the automatic and instantaneous influence of mutual information exchange on joint actions, an important element in social interaction, cannot be examined using such paradigms (Konvalinka & Roepstorff, 2012).

Four fMRI hyperscanning studies challenged real-time interaction by creating scenarios enabling mutual gaze between two persons in joint attention paradigms (Bilek et al., 2015; Koike et al., 2016; Saito et al., 2010; Tanabe et al., 2012). Saito et al. (2010) set up a complex experimental paradigm allowing live video images of the participants' eyes and eyebrows, therefore one partner could follow the direction of the other's gaze towards the target object. After 2 years, the same group (Tanabe et al., 2012) utilized this paradigm to study patients with autism spectrum disorder (ASD). Prominent pair-specific interpersonal neural correlations were found in the right inferior frontal gyrus (IFG) of normal–normal dyads, but were reduced in ASD–normal dyads, indicating the right IFG's involvement in shared intention during eye contact. Recently, the group further expanded their fMRI hyperscanning research by investigating the neural underpinnings of shared attention in the context of learning (Koike et al., 2016). They adopted a 2-day experimental paradigm in which unknown dyads performed a mutual gaze task (MG1) followed by a joint attention (JA) task on the first day (Day 1); several days later (Day 2), the dyads performed a mutual gaze task (MG2) followed by a control gaze task (VIDEO, gazing at recorded video of the partner during MG1). Inter-brain synchrony was found in various brain regions (e.g., right middle temporal gyrus, bilateral IFG) during the real-time mutual gaze period, but not during the video period. Moreover, inter-brain synchrony in the right IFG featured a significant increase during MG2 relative to MG1 (enhanced by the JA task); no enhancement of inter-brain synchrony was found without JA (Experiment 2), or in cases where JA was administered when the partner was changed (Experiment 3). These findings indicate the possible role of the right IFG in generating and preserving shared attention. Another group (Bilek et al., 2015) developed a sophisticated hardware setup—an immersive audiovisual interface between linked fMRI scanners—to make online eye signal exchange possible, and this paradigm allowed switching roles (sender and receiver of eye gaze) between participants. They reported significant neural coupling between the interacting dyads' right temporoparietal junction (TPJ), a key region for social interaction. These novel paradigms give rise to real-time exchange of eye gaze and may be extended to future exploration of joint action/attention. Although mutual exchange of eye gaze is only one facet of social interaction and such eye contact may be less flexible inside the fMRI scanner, this is certainly a significant step for interactive social neuroscience with fMRI. Hyperscanning fMRI allowed for the collection of data during real-time social interaction, but not during offline situations: data in the latter circumstance cannot be obtained using single-brain fMRI recording.

Indeed, two-person fMRI studies are difficult to perform, as two fMRI scanners are seldom available in one institute using the same LAN, and each participant is required to lie motionlessly in the scanner while being able to interact with another participant. Using a computer interface has the potential to alleviate this issue, but brings about additional problems, such as time lags and ecological validity (King-Casas et al., 2005). In addition, different characteristics of different fMRI instruments at different sites could induce a considerable inter-device variance (Montague et al., 2002). Complex calibration is required, but is not sufficient. Recent attempts using dual-coil setups in a single fMRI scanner with two participants lying side-by-side (Lee, 2015; Lee, Dai, & Dix, 2010; Lee, Dai, & Jones, 2012) or face-to-face (Hari, Henriksson, Malinen, & Parkkonen, 2015) will likely help to resolve the above-mentioned problems. However, due to low temporal resolution and strict limitation on the natural movements of participants, it is nearly impossible for fMRI to record brain activities during social interactions as ecologically as in daily life (Koike, Tanabe, & Sadato, 2015).

MEG Hyperscanning

MEG hyperscanning studies emerged recently to investigate brain-to-brain interactions with high temporal resolution and reasonable spatial resolution. The first MEG hyperscanning study was performed by Baess et al. (2012). They presented a novel method to realize a distant MEG-to-MEG link with accurate synchronization: two participants at separate laboratories 5 km apart communicated with each other in real time via an audio connection with negligible delay and jitter. Recently, the same group updated their MEG hyperscanning apparatus by including a video connection between the dyads and replacing the landline-based connection with an Internet link. The improved equipment enabled audiovisual interaction with minimal delay (~130 ms, one-way) and no impediments to smooth, natural communication regardless of large geographical distances between dyads (Zhdanov et al., 2015).

Hirata et al. (2014) developed a dual audio-visual presentation system that allowed for real-time face-to-face interaction—permitting the two parties to see each other's facial expressions—between a mother and her child through a mirror system during MEG hyperscanning. This system was the first MEG hyperscanning system to be administered in a single shielded room; and it can be generalized to the simultaneous recordings of inter-brain activities between adult participants. The same group extended their study by investigating neuromagnetic couplings between children with ASD (48–94 months old) and their mothers during task-free face-to-face spontaneous non-linguistic interactions using this MEG hyperscanning system (Hasegawa et al., 2016). They found that the degree of MEG mu suppression in the right precentral area of both the mothers and children was correlated with the mothers' social ability, as well as specific traits of the children with ASD. Moreover, they demonstrated a significant correlation between the strength of mu suppression in the mothers and their children. Irrespective of its size, MEG hyperscanning is capable of providing high-resolution spatio-temporal profiles of neural activities during fast-paced social interactions. In addition, the MEG device is child-friendly and has potential for future studies that aim to track inter-brain couplings between mothers and their children.

EEG Hyperscanning

Following the first dual EEG study (Duane & Behrendt, 1965), the technique was largely abandoned for several decades due to EEG's insufficient spatial resolution at the time. However, the concept of EEG hyperscanning underwent a resurgence about a decade ago as a result of dramatic technological progress. Recently, EEG hyperscanning studies have prospered due to EEG's distinguished temporal resolution, relatively low cost, high portability, and significantly shorter time lags between systems. These merits have made EEG hyperscanning popular in social interaction studies, particularly for those involving moment-to-moment interpersonal coordination in a natural environment.

Turn-based interaction. To our knowledge, after the attempt of Duane and Behrendt (1965), the first significant EEG hyperscanning studies were launched by F. Babiloni and Astolfi's group, adopting a four-player (two teams of two players) Italian card game similar to the international game of Bridge (Astolfi, Toppi, et al., 2010; F. Babiloni, Cincotti, et al., 2007; F. Babiloni et al., 2006). These studies evaluated inter-brain communication by computing inter-brain functional connectivity between selected regions of interest from interacting brains. By comparing the patterns from different pairs of brains (team colleague or not), Astolfi, Toppi, et al. (2010) reported that only players from the same team exhibited a significant functional link, and this functional connectivity was predictive of successful card choosing. Furthermore, the same group employed a variety of interesting games, such as Prisoner's Dilemma (Astolfi et al., 2009, 2011; Astolfi, Cincotti, et al., 2010b; F. Babiloni, Astolfi, et al., 2007; De Vico Fallani et al., 2010) and Chicken's Game (Astolfi, Cincotti, et al., 2010a), to probe cerebral processes related to decision-making in the game theory context. By applying advanced graph theory measurements to the inter-brain connectivity, De Vico Fallani et al. (2010) provided evidence for the possibility of predicting the outcome of the joint decisions of the dyads on the basis of the EEG hyperscanning data, and the prediction accuracy was greater than 90%. They also suggested that inter-brain hyperconnectivity may be an indicator that can predict the strategies used by the two brains in social interaction.

Kawasaki, Yamada, Ushiku, Miyauchi, and Yamaguchi (2013) used EEG hyperscanning to study brain rhythm synchronization between two persons engaged in an alternating verbal task in which they were required to list letters of the alphabet in sequence. Twenty dyads performed the task before and after they completed an individual training session wherein the partner is a robot-like computer. The authors reported significant enhancement in inter-person neural and verbal synchronization as a result of the training, and claimed that such augmentation may reflect the emergence of empathy for the partner's speech rhythms.

Compared to the experimental paradigms used in the fMRI studies reviewed above, these EEG hyperscanning studies have situated multiple persons in more natural interactions without fixed roles (sender and receiver), and the interactions have taken place in real-world settings rather than through a hardware interface. These studies allowed for the investigation of neural bases underlying inter-brain communication in the order of milliseconds due to EEG's fine temporal resolution; however, the interpersonal behavioral coupling did not occur on the millisecond scale, but in a turn-based manner (Konvalinka & Roepstorff, 2012).

Ongoing mutual interaction. In addition to the above-mentioned turn-based face-to-face interactions, EEG hyperscanning has also been widely applied in studies of dynamic ongoing interpersonal coordination, such as finger/hand movement synchronization (Dumas, Nadel, Soussignan, Martinerie, & Garnero, 2010; Naeem, Prasad, Watson, & Kelso, 2012; Tognoli, Lagarde, DeGuzman, & Kelso, 2007), simultaneous music performance (C. Babiloni et al., 2011, 2012; Lindenberger, Li, Gruber, & Müller, 2009; Müller, Sänger, & Lindenberger, 2013; Sänger, Müller, & Lindenberger, 2012, 2013), and verbal communication.

Tognoli et al. (2007) proposed the first research of such kind. In this study, two participants were asked to produce continuous, rhythmic finger movements, which can be either of their own style and pace or synchronized with their partner's finger actions, with or without vision of each other's hand. Dumas et al. (2010) proposed a similar experiment in which two participants were visually paired via a dual video system while producing hand gestures. Later, the same group from the Tognoli et al. (2007) study published a successive report of finger movement synchronization

(Naeem et al., 2012). Whilst different methods were used to evaluate the relationship between the two brains' responses, these studies reached a consensus in suggesting that interpersonal synchronized behavior modulates neural activity in the right centroparietal region (Dumas et al., 2010; Naeem et al., 2012; Tognoli et al., 2007), most likely within the human mirror neuron system (Tognoli et al., 2007), and the observed inter-brain synchronization may be the result of several aspects of ongoing mutual interactions, such as anticipation of the partner's actions and turn-taking (Dumas et al., 2010).

Performing in musical ensembles, another kind of behavioral coordination, provides an interesting environment for studying social interaction. Lindenberger and colleagues (2009) performed a series of experiments to examine inter-brain neural effects when dyads of guitarists played a short melody cooperatively. Inter-brain oscillatory couplings were found prior to and during the coordinated actions for music production, which could be attributed to the similarities in sensorimotor feedback. More marked between-brain couplings were induced during periods that necessitated high demands on performance coordination (Sänger et al., 2012). In addition, musical roles (leader, follower, or listener) were found to modulate the inter-brain synchronization (Müller et al., 2013; Sänger et al., 2013). C. Babiloni and coworkers (2011, 2012) expanded this area by revealing brain signatures for emotional empathy during professional quartet music production. Although these studies recorded multi-subject EEG signals simultaneously, they did not investigate the possible synchronization between brains, but rather adopted a source imaging approach to locate the responsible brain region and calculated the correlation between this region's activity and the empathy trait measured by a psychometric test.

Interactions in an ecological setting. In recent years, great progress has been made in breaking the routine of hyperscanning social brains within a laboratory environment. Exploring social neuroscience during situations as naturalistically as possible in real-world settings is the current trend. Given its relatively low cost and high portability, EEG hyperscanning is flourishing in various social experiments with ecological settings. For instance, Toppi et al. (2016) performed a unique EEG hyperscanning study involving two pilots jointly executing a simulated flight during which the coordinated interaction between the two brains was a matter of life and death. They demonstrated that the pattern of inter-brain connectivity, primarily linking the frontal and parietal regions, was representative of the level of cooperation between the pilots during different stages of the flight. Specifically, during the take-off and landing phases, denser functional links between the two brains were related to the higher demand in cooperation.

Recently, Dikker et al. (2017) extended hyperscanning experiments beyond the laboratory, and validated the feasibility of investigating the neural signatures of a large group of interacting persons in ecologically natural settings over a long period. They used portable EEG units to simultaneously record neural signals from a class of 12 high school students during activities in their regular biology class for an entire semester (i.e., 11 sessions). The students were asked to rate four types of teaching styles based on how much they enjoyed them. These ratings were used to evaluate class engagement. Brainwave coherence between multiple individuals at various levels (i.e., the whole class, student–group, and student–student synchrony) was calculated to quantify neural synchronization. Their findings are not only informative, but also practical: (a) when students were highly engaged during the class, their brains exhibited enhanced synchronization; (b) such synchronization was not simply modulated by stimulus property, but was also influenced by individual differences in various aspects (e.g., teaching-style preference and social traits, such as empathy and group affinity); and (c) the students who had eye contact with each other before class exhibited increased student–student synchrony during the subsequent classroom activity. Although this study did not provide much information regarding the precise brain regions responsible for the observed neural synchronization, it demonstrated the potential of using portable inexpensive EEG headsets to reliably associate behavior and brain in an ecological setting, and therefore should inspire many future studies on social neuroscience (Bhattacharya, 2017).

As reviewed above, EEG research has established fundamentals of interactive social neuroscience. EEG, in particular portable EEG, is a suitable method for performing hyperscanning under social situations in ecological settings, as the participants can interact with each other with fewer restrictions on body movement. However, eye movements and muscle artifacts easily arise. The most evident shortcoming of EEG is its limited spatial resolution. Scalp EEG is not able to measure neuronal currents deep within the brain. Whilst the progress in mathematical techniques has allowed researchers to estimate the source of EEG signal, precise location is nearly impossible to achieve (Hari, Himberg, Nummenmaa, Hamalainen, & Parkkonen, 2013; Koike et al., 2015). The issue is aggravated when there are multiple sources, or if the source lies in deep brain structures (Grech et al., 2008). The majority of brain rhythms originate from multiple sources, the dominance of which varies rapidly, in the order of merely hundreds of milliseconds. Even for those most prominent brain rhythms, their sources are difficult to discriminate (Hari et al., 2015). Therefore, EEG does not appear to be a good candidate to accurately determine the spatial profile of the inter-brain links involved in social interactions (Koike et al., 2015).

fNIRS Hyperscanning

Coordinated action. fNIRS hyperscanning is a novel trend in current social neuroscience. The present review summarizes such studies (Table 1) by categorizing interaction types and pinpointing on some noteworthy study. For detailed methodology for each experiment, please refer to Table 1. The first fNIRS hyperscanning study was recently published (Funane et al., 2011). The authors used two portable 22-channeled fNIRS instruments to simultaneously record the hemodynamic responses in the prefrontal cortex (PFC) of six dyads whilst they were engaged in a cooperative button-press task with feedback and without feedback (control condition). Two participants sat face-to-face across a table, and pressed a button after counting to 10 s in their own mind following an auditory cue. The authors detected enhanced spatiotemporal covariance of oxygenated hemoglobin (oxy-Hb) in the PFC of the two brains when the dyads' performance on the cooperative task was improved (i.e., a shorter interval between their respective button presses). This finding suggests that people's inter-brain synchronization is associated with their performance during cooperative action.

Cui, Bryant, and Reiss (2012) promptly took the relay baton of fNIRS hyperscanning by using a similar temporally synchronized motor task performed by 11 pairs of participants. Specifically, two participants, sitting side-by-side, were asked to press a button as soon as possible following the appearance of a visual cue. Two types of tasks (cooperative and competitive) were adopted. In the cooperative task, the participants were instructed to make the button-press as synchronously as possible, with the aim to reach a time difference shorter than a pre-defined threshold. In the competitive task, they had to press a button before their competitor did to gain a point. In both tasks, the outcome of each trial was visually fed back to the participants. The inter-brain coupling was quantified by wavelet transformation coherence (WTC), a measure of the cross-correlation between two hemodynamic waveforms as a function of time and frequency. The authors found that the coherence between the hemodynamic responses from the two participants' right superior frontal cortices increased during cooperation but not during competition, which could not be simply explained by the resemblances in action, as the button press was more temporally synchronized in the competitive condition. In addition, for

Table 1 List of the analyzed fNIRS hyperscanning studies

Reference (year)	Interaction type	Task description	fNIRS setup & probe setting	Participants	Analysis method	Results
Funane et al. (2011)	Face-to-face, cooperative	Button press minimizing time difference	Portable 22 CH R&L-PFC	6 dyads	Covariance, CC	PFC: Cov. ↑ during cooperation Correlation between the degree of IBS and task performance.
Cui, Bryant, and Reiss (2012)	Side-by-side, cooperative/ competitive	Button press minimizing time difference	22 CH R&L-PFC	11 dyads	WTC	R-SFC: IBS ↑ during cooperation but not competition. Correlation between the degree of IBS and task performance in cooperation only.
Dommer, Jager, Scholkmann, Wolf, and Holper (2012)	Side-by-side, cooperative, turn-based	Dual *n*-back Single *n*-back	Wireless 4 CH L-PFC	4 dyads 7 singles	WTC, BA	L-PFC: IBS ↑ during cooperation
Holper, Scholkmann, and Wolf (2012)	Face-to-face Imitation	Finger-tapping Imitation	Wireless 4 CH L-PMC	8 dyads	WTC, GC	L-PMC: IBS ↑ during imitation. The brain signal of the model G-caused that of the imitator to a greater extent as compared to vice versa.
Holper et al. (2013)	Face-to-face, turn-based	Teacher–student dialog interaction	Wireless 4 CH L-PFC	17 dyads	BA, CC	L-PFC: IBS ↑ in successful teaching. Activity: successfully taught students < unsuccessfully taught students
Duan et al. (2013)	Side-by-side, competitive	Neural feedback (competition game)	22 CH, L-SMA	1 dyad	CC	L-SMA: correlation ↓ when one participant was winning the game as compared to a draw situation.
Jiang et al. (2012)	Face-to-face/ back-to-back, turn-based	Verbal communication	20 CH L-FTPC, 3 CH L-DLPFC	10 dyads	WTC	L-IFC: IBS ↑ during face-to-face but not back-to-back conversation.

Table 1 Continued

Reference (year)	Interaction type	Task description	fNIRS setup & probe setting	Participants	Analysis method	Results
						The degree of IBS reliably predicted the occurrence of non-verbal interactive behaviors.
Jiang et al. (2015)	Face-to-face, turn-based	Three-person leaderless group discussion	10 CH L-IFC, L-TPJ	11 triads	WTC, GC	IBS in L-TPJ: leader–follower > follower–follower. Leadership can be successfully predicted basing on the IBS and communication behaviors shortly after the conversation onset.
Osaka et al. (2015)	Face-to-face/ face-to-wall, cooperative	Singing/humming together	34 CH R&L FTPC	15 dyads singing/ 14 dyads humming	WTC	L-IFC: IBS ↑ in the cooperative singing/ humming condition irrespective of face-to-face or face-to-wall; R-IFC: IBS ↑ for humming only.
Liu et al. (2016)	Face-to-face cooperative/ obstructive turn-based	Jenga game with verbal communication	19 CH R-PFC, R-STS	8 dyads	WTC	BA8: IBS ↑ during both cooperative and obstructive interactions; BA9: IBS ↑ during cooperative interactions only
Nozawa, Sasaki, Sakaki, Yokoyama, and Kawashima (2016)	Face-to-face cooperative turn-based	Natural verbal game	Wireless 2 CH FP	12 quadriads	WTC	FP: IBS ↑ during cooperation
Hirsch, Zhang, Noah, & Ono (2017)	Online interactive/ offline non-interactive	Eye contact	42 CH, both hemisphere	19 dyads	WTC	IBS: Interactive (eye-to-eye) > non-interactive (eye-to-picture) in multiple areas in the left hemisphere (superior temporal, middle temporal,

Table 1 Continued

Reference (year)	Interaction type	Task description	fNIRS setup & probe setting	Participants	Analysis method	Results
						supramarginal gyri, pre- and supplementary motor cortices).
Cheng, Li, and Hu (2015)	Side-by-side, cooperative/ competitive	Button press minimizing time difference	22 CH PFC	45 dyads	WTC	Frontal: IBS ↑ in opposite-sex dyads, but not in same-sex dyads. In opposite-sex dyads only, significant correlation between IBS changes and degree of cooperation.
Baker et al. (2016)	Face-to-face (divided by two PC displays), cooperative	Button press minimizing time difference	19 CH R-PFC, R-TC	111 dyads	WTC	R-TC: IBS ↑ in female–female dyads, R-IFC: IBS ↑ in male–male dyads, For same-sex only, IBS was correlated with task performance.
Pan, Cheng, Zhang, Li and Hu (2017)	Side-by-side (divided by a partition), cooperative	Button press minimizing time difference	22 CH R-frontoparietal	49 mixed-sex dyads (Lovers, friends, strangers)	WTC, GC	R-SFC: IBS ↑ in lover dyads, which also significantly correlated with their task performance. Stronger directional synchrony from females to males than vice versa.

Note. CH = channel; L = left; R = right; IBS = inter-brain synchrony; PFC = prefrontal cortex; SFC = superior frontal cortices; PMC = premotor cortex; SMA = somatosensory area; FTPC = frontal temporal and parietal cortices; DLPFC = dorsolateral prefrontal cortex; IFC = inferior frontal cortex; TPJ = temporal–parietal junction; STS = superior temporal sulcus; FP = frontopolar; TC = temporal cortex; WTC = wavelet transform coherence; GC = Granger causality; BA = block average; CC = correlation coefficient.

the cooperative task only, the coherence increment was associated with improved performance. Based on this evidence, the authors concluded that brain-to-brain coherence may be a proxy for humans' cooperative behavior. Interestingly, this study also performed individual time series analysis but failed to reveal any task-specific patterns of the hemodynamic response. This striking contrast underlines the necessity of both recording and analyzing multi-subjects' brain signals, which may provide additional information for the study of social neuroscience (F. Babiloni & Astolfi, 2014).

As pioneers of wireless fNIRS hyperscanning, Dommer, Jager, Scholkmann, Wolf, and Holper (2012) developed an unconstrained (no disturbing cables) hyperscanning setting in which two four-channeled wireless fNIRS devices were used to simultaneously record hemodynamic responses in the left PFC of participants during either cooperative or independent performance of an *n*-back task. Signal processing was focused on the changes in total hemoglobin (total-Hb) concentration (total-Hb = oxy-Hb + deoxygenated-Hb [deoxy-Hb]). Traditional block-averaged (total-Hb) revealed that the hemodynamic response was larger for paired players than for single players. WTC analysis revealed that inter-brain coherence increased in the left PFC during joint task performance. This increase was observed in both the heart rate frequency and the low-frequency oscillations (which underpin joint behaviors).

Using the same wireless fNIRS setup as Dommer et al. (2012), the same research group attempted to identify the origin of between-brain neural synchronization as participants engaged in a paced finger-tapping imitation task (Holper, Scholkmann, & Wolf, 2012). In the imitation task, one participant (the model) was asked to tap right-hand fingers rhythmically (either self-paced or auditory stimulus-paced) on a keyboard, and the order of fingers used was freestyle; the other participant (imitator) was required to imitate the model's finger tapping. In the control task, the two participants performed the finger-tapping task alone but with the same pacing mode pattern (self-paced or auditory stimulus-paced). WTC analysis of total Hb revealed increased between-brain coherence in the left premotor cortices during the imitation task, and the coherence was more remarkable when the imitation was self-paced compared to stimulus-paced. In addition, Granger causality (GC) analysis revealed that GC in the imitation task was larger than in the control task, and the hemodynamic responses of the imitator adapted to that of the model. This study is noteworthy for its use of GC to identify the original source of neural synchronization.

Real-world social interaction. Prior to the previously reviewed EEG hyperscanning study during multi-person classroom activities (Dikker et al., 2017), Holper et al. (2013) conducted the first hyperscanning experiment of teacher and student interaction using wireless fNIRS. Block-averaged hemodynamic responses revealed that students who obtained successful knowledge transfer exhibited less activity in the left PFC region than those who did not acquire the knowledge. Correlation coefficients between teacher and student demonstrated significant inter-brain coupling in the left PFC region when the teaching was successful. This study has paved the way for subsequent exploration of brain-to-brain connectivity involved in realistic complex educational interactions.

In order to investigate the relationship between multi-person neural synchronization and social behaviors, Duan et al. (2013) built an online *cross-brain neurofeedback* experimental platform using fNIRS and validated it with a two-person neurofeedback experiment. After successful neural feedback training, two participants were asked to actively imagine physically participating in a competitive tug-of-war game. They were instructed to refer to the visual feedback information and use any learnt mental strategy (such as kinesthetic motor imagery) during the fighting rounds to defeat their opponent. A rope with a ribbon in the middle was displayed on the screen. The position of the ribbon was determined by the difference between the amplitudes of the two participants' brain signals (average oxy-Hb changes) in the left sensorimotor area. The online data analysis confirmed that the participants were able to mentally shift the ribbon. Interestingly, the offline data analysis revealed that the correlation of the oxy-Hb changes decreased when one participant was winning the game as compared to a draw situation. Although only one dyad was hyperscanned in this preliminary study and further validation is needed, it is the first study to extend the application of the hyperscanning technique to a brain–computer interface.

Jiang et al. (2012) corroborated the unique quality of face-to-face communication using fNIRS hyperscanning whilst participant pairs were involved in four types of real-time conversation tasks controlling two conditions (i.e., face-to-face vs. back-to-back, monologue vs. dialogue). WTC analysis revealed that significant inter-brain activity occurred only in the face-to-face dialogue condition over the left IFG. Importantly, this study combined brain activity with videotaped behavior data and disclosed that the degree of IFG coherence reliably predicted the occurrence of non-verbal interactive behaviors, such as body gestures and turn taking.

The same group extended their fNIRS hyperscanning research to further study the neural basis of leader emergence, an essential feature of human society, during realistic three-person verbal communication (Jiang et al., 2015). WTC analysis showed that interpersonal neural synchronization (INS) of leader–follower was significantly stronger than that of follower–follower in the left TPJ. In addition, combining the INS results with behavioral video data provided further information in that the quality, but not the frequency, of the leader's communication contributed to the increased INS. Notably, GC analysis revealed that leadership can be successfully predicted based on the INS and communication behaviors shortly (~30 s) after the onset of the conversation. Based on this evidence, the authors concluded that leaders emerge by synchronizing their neural activity with that of followers through their diplomatic communication skills and competence to achieve a unanimous group decision.

Another recent study (Osaka et al., 2015) examined whether the neural synchronization mechanism functions differently when two participants are engaged in another type of verbal/vocal interaction—cooperative singing/humming—a type of semi-verbal interaction. The participant dyads performed the singing/humming tasks either face-to-face (FtF) or face-to-wall (FtW) in a cooperative manner (sing/hum a song together). WTC results revealed that the inter-brain coherence in the left IFG increased significantly in the cooperative singing/humming condition, compared to the singing/humming alone condition, irrespective of FtF or FtW, whilst the right IFG showed an increased inter-brain coherence for humming only. These findings suggest that the neural synchronization in the participants' right IFGs may result from non-verbal coordination, such as humming (no lyrics, vocal), whereas the between-brain couplings in the left IFG may be due to verbal coordination.

Liu et al. (2016) designed an fNIRS hyperscanning experiment in a naturalistic, interactive setting using a non-computerized Jenga game. Four conditions were used for each dyad: two patterns of interactive game (cooperative and obstructive), during which oral communication was permitted; one independent game; and one dialog-only condition. WTC analysis revealed that, compared to independent game and dialog-only conditions, inter-brain coherence was observed in the posterior region of the right middle and superior frontal gyri (particularly BA8) during both cooperative and obstructive interactions, suggesting BA8's role in common goal-oriented social decision-making when two persons interact. Interpersonal neural synchrony in the dorsomedial PFC (BA9) was observed during cooperative interactions only, indicating that BA9 might be involved in cases when theory-of-mind is necessary during interaction. This study made efforts to precisely determine the spatial profile of inter-brain synchronization induced by natural social interaction. Approaches such as registering to a standard

MRI brain template and using a structural node-based spatial registration method were adopted for intra-dyad and inter-dyad analyses, respectively.

Researchers have made further attempts to improve the precision of fNIRS hyperscanning. For instance, Nozawa, Sasaki, Sakaki, Yokoyama, and Kawashima (2016) carried out a wireless fNIRS hyperscanning experiment wherein four-person groups were engaged in a cooperative verbal word chain game, and provided a technical basis for future hyperscanning studies by introducing innovative methods of data recording and analysis. The wireless fNIRS device used one light source and two light detectors, forming two channels, to monitor both the cerebral hemodynamic response and the systemic blood-flow signal in the frontopolar region. The authors performed sophisticated data preprocessing, such as removal of artifacts due to superficial blood-flow and body movements. WTC analysis validated increased inter-brain synchrony in the frontopolar region during the communicative session compared to the non-communicative session. Their preprocessing approach substantially improved the sensitivity to capture communication-induced inter-brain synchrony, while, as the authors stated, caution should be taken to avoid excessive removal of signals of neural origin.

Recently, Hirsch, Zhang, Noah, and Ono (2017) utilized more detailed and sophisticated data-interpretation methods to investigate the functional specificity (intra-brain) and functional synchrony (inter-brain) of online eye contact, a primary element of real-world interaction, using fNIRS hyperscanning. The authors pioneered a novel level of global sampling of fNIRS by covering the majority of the brain region, with the exception of the occipital area of each dyad. Moreover, a novel dual eye-tracking system with monitoring cameras embedded into eyeglass frames for each participant was used during fNIRS recording and synchronized to the fNIRS signals. Participants were asked to either make eye-to-eye contact with their partners (online interaction) or gaze at the eyes of a face on the screen (eye-to-picture, offline interaction). Multidimensional analyses focused on the deoxy-Hb and revealed that, relative to eye-to-picture gaze, eye-to-eye contact led to increased activity in a left frontal cluster of regions (including pars opercularis, pre- and supplementary motor cortices, and the subcentral area) in the individual's brain, which is also functionally connected to other regions, such as the left superior temporal gyrus and primary somatosensory cortex. In addition, compared to eye-to-picture gaze, eye-to-eye contact elicited increased partner-specific between-brain coherence in the left superior temporal, middle temporal, supramarginal gyri, as well as pre- and supplementary motor cortices. As both intra- and inter-brain neural correlates of eye-to-eye contact are associated with previously established language systems, the authors suggest integrated face-to-language processing during online eye contact.

Effects of sex and relationship of dyads.

Cheng, Li, and Hu (2015) and Baker et al. (2016) examined how the sex composition of an interacting dyad influences the behavior and brain activity during cooperative interaction. Both studies adopted the computer-based button-press task, yet obtained different results. Cheng et al. reported that only opposite-sex dyads exhibited cooperation-induced inter-brain synchrony in the frontal regions, and the degree of inter-brain synchrony was significantly correlated with the degree of cooperation. However, Baker et al. found that cooperative interaction led to inter-brain synchrony in the right temporal cortex of female–female dyads and in the right inferior PFC of male–male dyads, but not in the opposite-sex dyads. An additional finding of this study was that the inter-brain synchrony was positively correlated with task performance (degree of cooperation) for same-sex dyads only. As the two studies focused on different brain regions, it is plausible that both same-sex and opposite-sex dyads would exhibit increased inter-brain synchrony due to cooperative behaviors, nonetheless, in different brain regions. Future studies using whole-brain measurement may elucidate this sex effect on interpersonal neural synchronization.

Furthermore, Pan, Cheng, Zhang, Li, and Hu (2017) investigated the interacting partners' relationship effect on cooperation-induced interpersonal neural synchronization using the cooperative button-press task (Cui et al., 2012). They recruited mixed-sex dyads of lovers, friends, and strangers. In addition to improved task performance in lovers compared to friends and stranger dyads, WTC analysis revealed that lovers also exhibited increased inter-brain synchrony in the right superior frontal cortex, which significantly correlated with their degree of cooperation. GC analysis revealed stronger directional synchronization from females to males than vice versa, indicating a leading role for females in romantic relationships during cooperative interaction.

Summary of fNIRS hyperscanning. All the above-reviewed fNIRS hyperscanning studies have endeavored, by utilizing either innovative paradigms or novel data analysis methods (or both), to elucidate the neural processes underlying real-world interaction that are difficult to investigate using fMRI hyperscanning. These studies, in general, demonstrated that cooperative interaction enhances synchronized cerebral activities and detected the engaged brain regions. They have provided additional insights into EEG hyperscanning by disclosing the functional specificities of various natural social interactions. For instance, enhanced interpersonal neural synchronization was often found in the right hemisphere, primarily the right PFC, during cooperative behaviors with coordinated goals, whereas verbal-based communication typically induced inter-brain coherence in the left hemisphere, primarily the left PFC and TPJ. Additionally, based on fMRI and fNIRS literature, either the right or left IFG appears to be a critical area for interactive human activities. Unfortunately, most of the fNIRS studies did not fully utilize the advantageous spatial resolution and have provided limited information regarding the brain region of interest. Consequently, at this point, we would not attempt to determine precise brain areas and networks of interactive social science. Given fNIRS's moderate spatial resolution, only a few recent studies—for example, Hirsch et al. (2017) and Liu et al. (2016)—have attempted to precisely discriminate brain areas involved in realistic person-to-person interactions. Furthermore, fNIRS studies with a few channels should also be careful with this issue, and such studies should first determine the significant brain regions for attaching the probe. As has been found from fMRI and multi-channel fNIRS studies, some brain regions are crucially engaged in a certain cognitive processing of interaction. Determination of the target brain area and channel localization should be based on these studies. Future studies should take advantage of fNIRS's precision in localizing brain functions by employing spatial estimation methods (e.g., virtual registration; Tsuzuki et al., 2007) and develop more advanced approaches for data acquisition and interpretation to further extend the potential of fNIRS in social cognitive research.

Neuroimaging Social Interactions of Young Populations

Infants' Brain Responses to Live Social Stimuli

While we have already discussed the significance of live stimuli, neuronal evidence supporting the impact of live stimuli has been reported by studies using various measurement modalities, such as fNIRS (Shimada & Hiraki, 2006), EEG (Jones, Venema, Lowy, Earl, & Webb, 2015), and MEG (Jarvelainen, Schurmann, Avikainen, & Hari, 2001). An fNIRS study of infants, for instance, compared live and non-live stimuli of human action and observed a stronger response to the live stimuli. This is not an interactive paradigm, thus the larger activation to the live stimuli may relate to factor (a) and (d) (Figure 2), as stated in the first section. To the best of our knowledge, hyperscanning of the infant brain has rarely been performed; we have therefore focused on single recording of fNIRS studies with live interactive stimuli.

Four fNIRS studies have examined the social cognitive brain activity of infants using live social stimuli. Although these studies did not employ hyperscanning methods, the majority used interactive paradigms. Pioneering work was reported in a study of fNIRS measurement of the prefrontal area during live joint attention episodes by Naoi, Kobayashi, Hara, Yamamoto, and Kojima (2008; also reported in a book chapter: Minagawa-Kawai, Naoi, & Kojima, 2009). Joint attention is a crucial milestone for development of infants' social and communicative abilities, and is defined as a shared attention of two individuals for one object, which reflects ability to understand another's intention. Naoi et al. (2008) performed live episodes of responding to joint attention (RJA) and initiating joint attention (IJA) to measure frontal hemodynamic activity with the event-related paradigm. Mothers held their infants (15 9-month-olds, age range: 7–12 months) with whom one experimenter interacted for RJA and IJA episodes. The results showed strong responses in the right lateral PFC and medial PFC areas to RJA, in contrast to strong selective activation in the dorsomedial PFC during IJA episodes. These results are consistent with fMRI studies with adults reporting engagement of the dorsomedial PFC for IJA (Mundy, 2003). This study was successful in capturing the cerebral response to interactive live stimuli, and suggested that infants' early cerebral substrates of intention develop at around 9 months. A recent study by Urakawa, Takamoto, Ishikawa, Ono, and Nishijo (2015) also focused on the prefrontal area, and measured the response to live peek-a-boo stimuli by comparing conditions of direct and averted gaze. The results of 7-month-old infants revealed a significant role of the dorsomedial PFC during live mutual gaze consistent with Naoi et al. (2008).

Two fNIRS studies examined activation in the frontal and temporal areas during social interaction. Although one of the standard methods to examine intention is joint attention, Lloyd-Fox, Szeplaki-Kollod, Yin, and Csibra (2015) used a unique method to investigate cerebral correlates of identifying communicative intention in 6-month-old infants. Two infants simultaneously participated in the experiment to interact with one experimenter. The conditional difference from the participating infant's view was whether the experimenter intended to communicate with him or the other infant. The experimenter would sing or speak with gestures to either one of the infants for each condition by differentiating direct eye gaze. They found stronger activations for the self condition in multiple regions of temporal areas. This study is noteworthy in its attempt to employ a naturalistic context; however, in such an ecological experiment, it was difficult to control various factors (i.e., speech, gestures, contingency) to determine the correlates of brain activation. Hakuno and Minagawa (2016) attempted to limit such factors with the use of a suitable baseline task. The study intended to observe brain responses to mutual gaze and contingency during structured play between an infant and an experimenter. The experimenter reacted to the infant's behavior in terms of eye gaze and contingent responsiveness for each condition. The results of 6–8-month-olds showed large responses in the TPJ and posterior superior temporal gyrus on the right side to the contingent condition. Although the TPJ's role in processing contingency is well known, this could be the earliest evidence of the TPJ's function. Importantly, such cerebral response to contingency in a social context may have been obtained due to the impact of interactive live stimuli.

Hyperscanning Mother–Infant Interaction

What makes it difficult? Interaction with a parent primarily fosters the fundamentals of social skills in human infants and children. Particularly, mother–infant bonding early in life has been shown to play a critical role for social cognitive abilities, including emotion regulation and social responsiveness (Feldman, 2015). Indeed, rich social stimuli interactively provided by a parent are linked to optimal behavioral and cognitive development (Cabrera, Fagan, Wight, & Schadler, 2011; Lugo-Gil & Tamis-LeMonda, 2008), unlike parental insensitivity, which resulted in increased risk of childhood psychopathology

(Murray, Halligan, & Cooper, 2010). Yet, less is known about the neurobiological basis underlying the parent–infant interaction, due to the methodological difficulty. The advent of the fNIRS system has provided an optimal solution, as it enables live measurement of the mother–infant interaction with reasonable spatial resolution. However, there are several significant difficulties in performing mother–infant hyperscanning, as reported by Minagawa-Kawai, Naoi, and Kojima (2009). One of the predicaments was the presence of artifacts in recordings due to facial movements: Mother–infant communicative interactions are always conveyed via facial gestures, including forehead and oral movements. These kinds of movements critically interfere with fNIRS signals. Among 10 mother–infant dyads tested, several mothers showed unusually large signals (Figure 3). The task in the block design included a baseline condition, wherein a mother showed a neutral face to an infant, and a target condition wherein, a mother positively interacted with an infant with a smile. The signal in Figure 3 appeared task-specific; however, deoxy-Hb as well as oxy-Hb exhibited an unusual rapid increase. This type of signal does not originate from the cerebral cortex, but from change of probe distance and/or probe separation from the skin due to facial movement. Systemic blood change due to induction of emotion may have partially contaminated the signals. Another difficulty involved fNIRS probe caps; even if infants (aged 8–12 months) accepted a probe cap attached to their foreheads, they occasionally disliked the NIRS caps on their mothers. These difficulties with hyperscanning of mother–infant interactions could not be overcome (Minagawa-Kawai, Naoi, & Kojima, 2009). This attempt yielded results similar to a rather conventional fNIRS study using prerecorded social visual stimuli of mother and infant, providing neuronal evidence of mother–infant attachment (Minagawa-Kawai, Naoi, & Kojima, 2009).

The above-mentioned issue regarding motion-related artifacts and systemic effects remains valid for hyperscanning fNIRS studies, regardless of the population type. However, as reviewed in the previous section, researchers have tried to avoid the issue by using suitable tasks for adult study. Even with child populations, a recent study by Reindl, Gerloff, Scharke, and Konrad (2016) successfully performed fNIRS hyperscanning under the setting of computer game play. Higher synchronized activations between a parent and child (aged 5–9 years) were observed in the left dorsolateral PFC area during the cooperation task relative to the competing task. This task, which does not always associate with facial movement, is an adaptive task to assess interaction between children and adults.

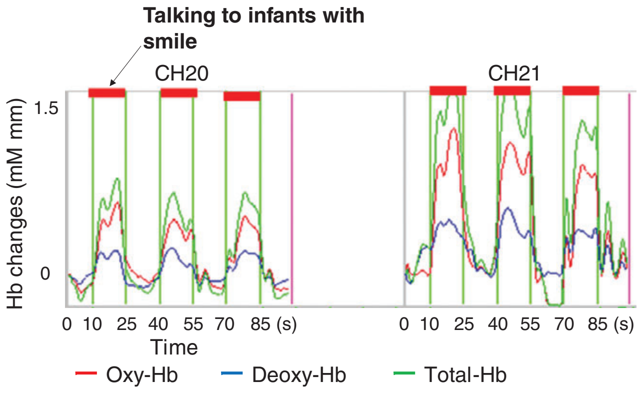

Figure 3 Hemoglobin changes predominantly elicited by motion artifacts during mother–infant interaction experiment.

However, this is not feasible for infant populations and populations with disabilities.

Synchronized brain activity between mothers and infants: Preliminary results and technical issues. It is known that human behaviors in nature tend to synchronize with others' movement, a phenomenon known as entrainment. This spontaneous synchronization involves various movements, such as walking, tapping, postural sway, and eye-blink (Okazaki et al., 2015; Shockley, Richardson, & Dale, 2009; Zivotofsky, Gruendlinger, & Hausdorff, 2012), which occur either explicitly or implicitly. Although the detailed neuronal basis underlying synchronization remains unclear, this motion-forming behavior may relate to the human mirroring system and/or self-organizing system, serving as a fundamental basis for human empathy (Koban, Ramamoorthy, & Konvalinka, 2017; Koehne, Hatri, Cacioppo, & Dziobek, 2016). It would appear that entrainment is characteristically observed in the most fundamental form of human dyad, mother and infant, as revealed by behavioral studies (Feldman, 2007, 2017). The degree of synchrony predicts infants' social development, such as self-control and empathy (Feldman, Greenbaum, & Yirmiya, 1999). Coherent physiological signals have also been observed for mother and infant. Specifically, cardiorespiratory activity was demonstrated to be synchronized between mother–infant dyads while infants lay on the mother's body (Van Puyvelde et al., 2015). Such synchronization is thought to be triggered by subtle perceptual cues, including eye gaze, subtle facial movement, and breathing, which may be processed implicitly.

Based on the findings reviewed above, it is now evident that examining mother–infant interaction without positive and spontaneous communicative signals is possible and meaningful. This allows for mother–infant hyperscanning free from several artifacts to be performed. Consequently, Minagawa (2016) carried out mother–infant hyperscanning during which mothers held their infants (holding condition) to compare to the control separation condition wherein an experimenter held the infants and the mothers were at rest. Infants were in an active sleep condition in both sessions. Each session lasted more than 5 min. Bilateral temporal area and frontal areas were measured using 44 channels for both the mother and the 3–4-month-old infants. Of the 20 participating dyads, the final data set included data from eight dyads, providing 4 min of clean data without artifacts. After preprocessing the data with the hemodynamic modality separation method (Yamada, Umeyama, & Matsuda, 2012) and wavelet-minimum description length, the mother and infant data were combined for each dyad (88 channels) to generate a time series of the data separated by condition. Independent component analysis–second-order blind identification (ICA-SOBI; Belouchrani, Abed-Meraim, Cardoso, & Moulines, 1997) was applied to the combined dyads' data in order to extract shared components across 88 channels. For components obtained from ICA-SOBI, we examined the difference of the components' amplitude between two conditions.

Figure 4 depicts preliminary results for holding versus control. Two components exhibited significantly larger amplitudes for the holding condition than for the control ($p < .05$, Wilcoxon-signed rank test). Figure 5 plots the time course of the component's amplitude and Figure 4 indicates where the component originated from and its amplitude of contribution to that component. The largest synchronization for the holding condition was observed in the mid-channel of the lowest channel line, which is assumed to be near the anterior orbitofrontal cortex (OFC) for both mother and infant. Namely, activation of the anterior left OFC was more strongly synchronized when mothers held their infants. As the OFC is known to be a significant cerebral area engaged in maternal attachment (Minagawa-Kawai, Matsuoka, et al., 2009; Schore, 2000), the results may further support its role. Other than that channel, large synchronizations were observed near the right PFC for mothers, while those for infants were in the right temporal and parietal areas, including TPJ. Unlike the correlation analysis or wavelet-coherence method generally used for fNIRS hyperscanning, ICA-SOBI allowed us to assess several components shared across different channels.

Although this is a preliminary study with limited participants, the results demonstrate that fNIRS has the ability to assess two-person synchronization, even in infants, with relatively good spatial resolution. As previously mentioned, synchronization relates to the self-organizing system and human empathy. Thus, fNIRS measurement of Hb synchronization in infants could be a powerful methodology for the developmental study of social neuroscience. In fact, using this method, hyperscanning between parents and infants at risk for ASD has been successfully performed at our laboratory. However, regarding the hyperscanning discussed above, several issues remain unresolved. One such issue is the analysis method. For the analysis, ICA-SOBI was used to extract hemodynamic activities shared between mother and infant; however, the hemodynamic time course differs between adult and infant (Minagawa-Kawai et al., 2011), most likely due to different rates of synaptogenesis and angiogenesis in the young developing brain. Thus, in discussing the synchrony, we require a novel analysis method that can detect synchrony with different frequencies. Further, the present method allowed for the extraction of shared components during a certain period of time (4 min in this experiment); such a time window was not sensitive

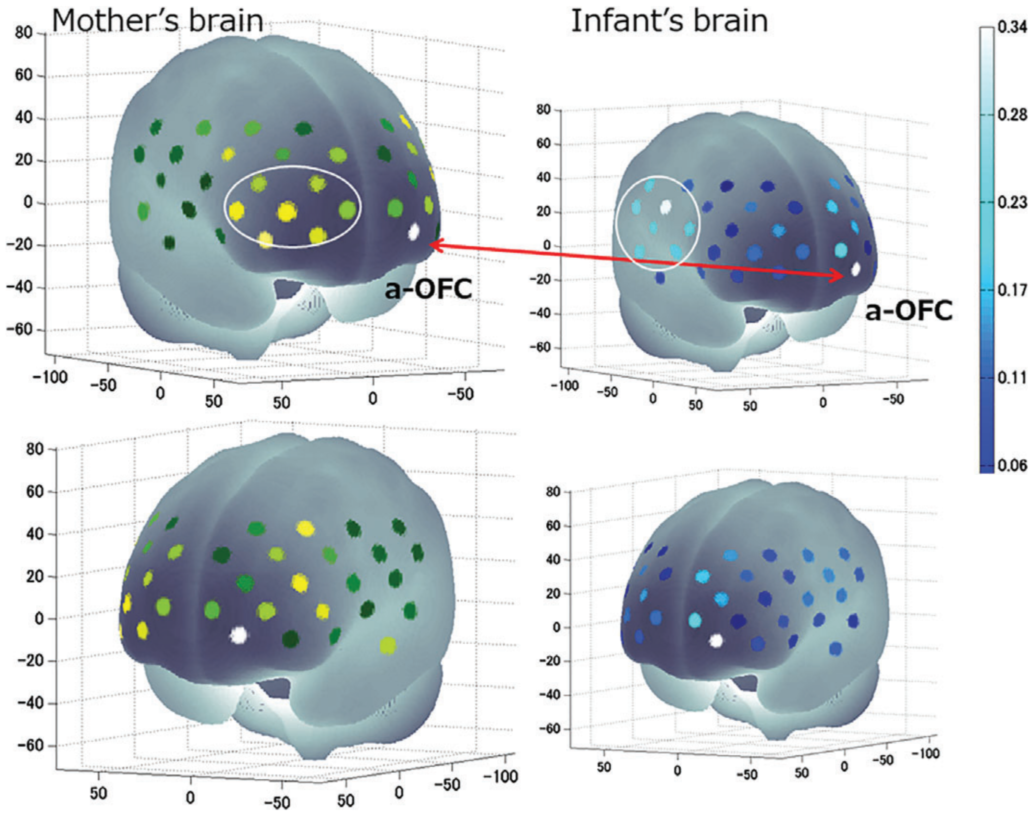

Figure 4 Brain synchronization when the mother held her infant. Amplitude of contribution to a synchronized component that is larger for the holding condition than the separate condition is plotted for mother and infant brains. Top panels indicate a view from the right side and bottom panels from the left side.

enough to detect a dynamic interplay between the mother and infant, which occurs over a relatively short period of time. As the aim of this experiment was to ascertain long-term synchronization, future studies should explore the dynamic aspect of mother–infant interaction further.

Mechanisms, Future Directions, and Conclusions

Mechanisms of Brain-to-Brain Coupling

Although hyperscanning of social brains is a burgeoning field, it has yielded limited insights into the mechanism of inter-brain coupling: the focus of many investigations that have used hyperscanning. However, on the basis of the studies reviewed previously, we would like to introduce a hypothetical mechanism for interactive brain systems, particularly focusing on synchronized neural activities.

The action–perception loop (Hari & Kujala, 2009) of the human brain appears to be one of the significant mechanisms that underlie synchronization; this loop works within the brain but also between different brains (Konvalinka & Roepstorff, 2012). Specifically, the behavior of individual A is tightly linked to the brain activities of individual B by eliciting B's mirror neuron system (MNS) activations and inducing automatic mimicry. On receiving B's contingent behavioral signals, A's brain is similarly affected; this results in causing a similar, contingent action. By exchanging such behavioral signals implicitly or explicitly, the inter-stimulus (action) interval between A and B would gradually decrease. As a result, their neural activities as well as behaviors would become in sync. This process was partly verified by a series of fMRI studies. Firstly, Sasaki, Kochiyama, Sugiura, Tanabe, and Sadato (2012) showed that the middle temporal gyrus (MTG) and IFG, which are known to be a fundamental neuroanatomy of MNS, are engaged in the automatic mimicry. In particular, connectivity between MTG and IFG was revealed to play a significant role in sending information of action execution and action perception. In fact, later fMRI hyperscanning studies indicated that IFG and MTG are the brain areas involved in the inter-brain coupling by consistently demonstrating synchronization of the right IFG of two persons during a joint attention task (Koike et al., 2015, 2016; Saito et al., 2010; Tanabe et al., 2012). The IFG synchronization appeared to be induced by behavioral synchronization of eye blinks, because amplitude of the IFG synchronization positively correlated with that of behavioral synchronization. Furthermore, intra-brain connectivity between MTG and IFG increased after a joint attention task and its increment correlated with the amplitude of the IFG synchronization within the dyad (Koike et al., 2016; Sadato, 2016). They further revealed that associative learning contributes to the construction of such synchronization networks (see the section on fMRI

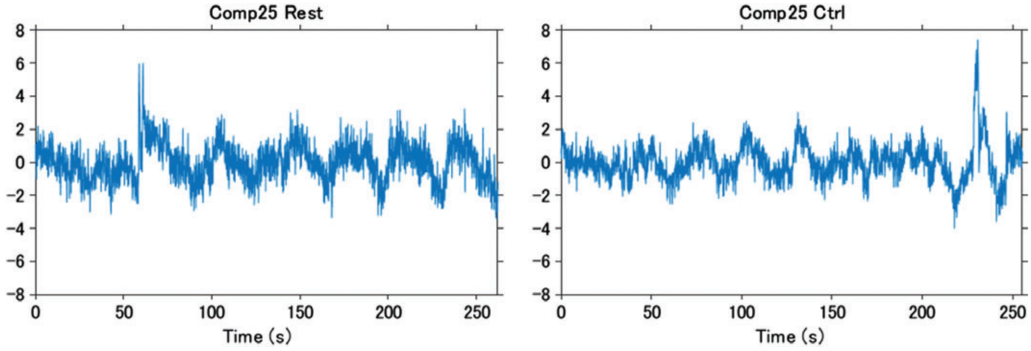

Figure 5 Time course of component amplitude for the mother–infant condition (left) and stranger–infant condition (right). These components are derived from all of the channels. This is an example of one dyad.

Hyperscanning, above, for more details). In summation, the IFG and MTG—as components of the MNS network—play crucial roles in inter-brain coupling during interaction (Figure 6).

Though its relation to the MNS network remains unclear, the mentalization network (MENT; Frith & Frith, 2006) is also proposed to be involved in inter-brain coupling (Schilbach et al., 2013) (Figure 6). Experiments on the interactive social paradigm have shown that activation of the MENT does not necessarily require emotional processing or explicit assessment of mental state (Schilbach et al., 2010), namely, MENT activates in response to eye gaze or presence of intention. This phenomenon may be referred to as *presence of mind*, as indicated by (d) in Figure 2. Results of infant fNIRS research on the live-interactive paradigm agree with this view. Naoi et al. (2008) and Urakawa et al. (2015) demonstrated strong activities of the dorsomedial PFC during the mutual gaze of joint attention tasks that did not accompany explicit emotional processing. Our fNIRS study supplies additional evidence supporting the dorsomedial PFC as a processor of sense of human mind: Using a live interactive paradigm, Hakuno (2018) measured responses of frontal and temporal areas of 6–7-month-old infants to human contingent stimuli (e.g., smile of the experimenter) in comparison to the responses of the aforementioned areas to non-human contingent stimuli (LED light). The study found that the dorsomedial PFC area evinced strong activation, as well as connections to the TPJ area, exclusively in response to human contingent stimuli. The effect was observed regardless of the valence of stimuli (positive and negative). Although these infant studies are not hyperscanning experiments and therefore lacking in sufficient evidence, some adult fNIRS hyperscanning reported synchronization of the dorsomedial PFC (Liu et al., 2016) and frontal pole areas that may recruit the medial PFC (Nozawa et al., 2016) only during cooperative tasks.

The TPJ is also a part of the MENT (Adolphs, 2009; Frith & Frith, 2006), and seems to provide an essential contribution to brain coupling: It distinguishes the signals addressed to self or others, and processes intentions and purposes of social signals to send to the MPFC (Gallese, Keysers, & Rizzolatti, 2004; Van Overwalle, 2009). A series of fNIRS studies using the live interactive paradigm (Hakuno, 2018; Hakuno & Minagawa, 2016) consistently showed the TPJ's role in processing contingency. Furthermore, an fMRI study (Bilek et al., 2015) and an fNIRS study (Jiang et al., 2015) reported inter-brain synchrony of TPJ during social interaction. Contingency is an important factor for interactive behavior as indicated by (b) in Figure 2.

As the network of reward processing is associated with the MENT, we assumed that it is also engaged in brain coupling. Social interaction itself is generally a rewarding process by which we can share feelings and experiences with others (Tomasello, 2009). Our preliminary study on mother–infant hyperscanning supported this interpretation by revealing inter-brain coupling of the OFC areas. Reward processing is critically related to associative

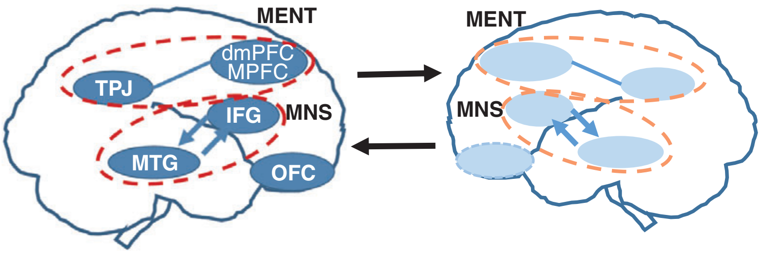

Figure 6 Brain areas that engaged in inter-brain coupling. MNS, MENT, and additional reward networks are cerebral substrates operating within the two-in-one brain system.

learning, which shapes the MNS network (Koike et al., 2016).

As evidenced by several studies, regardless of their measurement modality (Koike et al., 2016; Pan et al., 2017), inter-brain coupling is more easily observed between a familiar dyad than an unfamiliar dyad. Accordingly, more effective synchronization could be assumed between family members or colleagues in a professional performance, such as dance and music. Although such a synchronization network among familiar members could be regarded as an automatic process modulated partly in a top-down fashion, it could have been organized as a result of a bottom-up type of associative learning reported by Koike et al. (2016). Inter-brain coupling observed between a mother and her infant could present an example of this type of synchronization. Such a pre-established network could facilitate future human interactions. In this sense, inter-brain coupling would not always be the result of behavioral signal exchange, but that of a pre-organized network that can drive brain activity to enhance interaction. Other than such behavior-induced brain coupling, another type of top-down modulation may exist (Roepstorff & Frith, 2004) that may not accompany action perception.

To finalize this section regarding brain-coupling mechanisms, we will mention a temporal issue concerning the examination on the interactive brain. As previously reviewed, synchronization mediated by the action–perception loop emerges from exchanges of action signals within finite time windows. Thus, in many cases, the short time frame for each action cluster may inform the analysis window, particularly to analyze the causality of brain synchronization. However, once inter-brain activities are tuned and synchronized, long analysis time windows may better capture the synchronized components between two brains than observing dynamic changes.

Concluding Remarks

As described in this review, by following hyperscanning studies by EEG or fMRI, researches with fNIRS have played a dominant role in developing a new field of neurobiology: interactive social neuroscience. Although infant fNIRS hyperscanning studies with interactive paradigms have yet to be perfected, the studies reviewed above have demonstrated the potential of fNIRS to reveal the development of social cognitive abilities. This will eventually contribute to the disclosure of the ontogeny and phylogeny of the human interactive social brain.

Based on the evidence regarding adult interaction, it seems that this line of fNIRS research may diverge into two directions, one being mobile recordings for practical use. As reviewed in the second section, an fNIRS system with several channels has successfully observed social cognitive activities. With the technical advance of fNIRS instrumentation, we may be able to obtain the system and use probes with a more comfortable setting. This type of system could be utilized in various practical settings, such as education and marketing. Big data obtained by this modality would contribute to machine learning data for artificial intelligence.

The other direction is rather mainstream: basic research in social neuroscience. At present, the main interest of most fNIRS and EEG hyperscanning studies is determining the condition under which brain areas are in sync. This type of study would expand our knowledge and may yield an aforementioned practical use. However, as has been examined chiefly by fMRI studies, fNIRS studies should focus more on the basic mechanisms of interactive brains. As summarized in this review, MNS and MENT networks are two dominant mechanisms that contribute to inter-brain coupling. On the other hand, detailed mechanisms remain to be uncovered. Fortunately, fNIRS can measure most of these networks; fNIRS studies should therefore make the most of their advantage for live interactive experiments to clarify the two-in-one brain system. Defining the relationship between the MNS and MENT is one of the crucial issues in need of further investigation. Importantly, these networks will be uniquely revealed by hyperscanning with the interactive paradigm. Future studies should also investigate these interactive processes by showing causality, although there have already been some successful attempts at this. As stated in the introduction, bidirectional social interaction may involve feedforward and feedback processes between agents. There may be some global interactive social rule that depends on the social context and may crucially affect the MNS and MENT. Identifying the cerebral substrates underlying such processes, which may be dependent on the agent's personality and social background, would provide essential information for future research. To this end, simultaneous recording of behavioral and physiological data to correlate with fNIRS data will be beneficial. In addition, employing fMRI separately from fNIRS would be a reasonable option due to the higher spatial resolution and improved assessment of deep brain areas, including the reward network. Exploitation of fNIRS hyperscanning by more social neuroscientists in the fields of fMRI, EEG, or MEG would empower interactive social neuroscience in the future.

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(Received November 18, 2017; accepted May 7, 2018)